

The Clusters AgeS Experiment (CASE). Variable stars in the field of the globular cluster NGC 3201*

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ABSTRACT

The field of the globular cluster NGC 3201 was monitored between 1998 and 2009 in a search for variable stars. BV light curves were obtained for 152 periodic or likely periodic variables, 57 of which are new detections. Thirty-seven newly detected variables are proper motion members of the cluster. Among them we found seven detached or semi-detached eclipsing binaries, four contact binaries, and eight SX Phe pulsators. Four of the eclipsing binaries are located in the turnoff region, one on the lower main sequence and the remaining two slightly above the subgiant branch. Two contact systems are blue stragglers, and another two reside in the turnoff region. In the blue straggler region a total of 266 objects were found, of which 140 are proper motion (PM) members of NGC 3201, and another 19 are field stars. Seventy-eight of the remaining objects for which we do not have PM data are located within the half-light radius from the center of the cluster, and most of them are likely genuine blue stragglers. Four variable objects in our field of view were found to coincide with X-ray sources: three chromospherically active stars and a quasar at a redshift $z \approx 0.5$.

globular clusters: individual (NGC 3201) – stars: variables – stars: SX Phe – blue stragglers – binaries: eclipsing

1 Introduction

NGC 3201 is a nearby ($d=4.9$ kpc) globular cluster (GC), projected against the edge of the galactic disk at $l=277^\circ.2$ and $b=8^\circ.6$) in a field with an average reddening of $E(B-V)=0.24$ mag. Its core radius, half-light radius, concentration parameter, $[\text{Fe}/\text{H}]$ index, and radial velocity are equal to $1'.3$, $3'.1$, 1.29 , -1.59 and $+494.4 \pm 0.2$ km/s, respectively (Harris 1996, 2010 edition). The exceptional kinematic properties of NGC 3201 (extreme radial velocity and retrograde orbit around the center of Milky Way) strongly suggest an extragalactic origin for this object. However, as it exhibits no peculiarities in the chemical composition, its chemical evolution must have been similar to that of other galactic GCs (Muñoz et al. 2013). The proximity and low concentration make NGC 3201 an attractive target for detailed studies with ground-based telescopes. Unfortunately, photometric observations are seriously hampered by large differential reddening, with $E(V-I)$ varying by up to 0.2 mag on a scale of arcminutes (von Braun & Mateo 2000).

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*Based on data obtained with the Swope telescope at Las Campanas Observatory.

Early pre-CCD searches for variables in the field of NGC 3201, summarized by Clement et al. (2001), Mazur et al. (2003, hereafter M03), and Arellano Ferro et al. (2014), resulted in the detection of 100 objects, some of which were found to be nonvariable in later studies. The four CCD surveys that have been performed so far (von Braun & Mateo 2002, M03, Layden & Sarajedini 2003, and Arellano Ferro et al. 2014) reported an additional 24 discoveries. Altogether, 113 variable stars have been listed, consisting of 86 RR Lyr and 16 SX Phe pulsators, 3 eclipsing binaries, and 8 long-period/irregular variables). All of these presumed to be cluster members.

The 57 new variables presented in this contribution are a result of the long-term photometric survey conducted within the CASE project (Kaluzny et al. 2005) using telescopes of the Las Campanas Observatory. Section 2 contains a brief report on the observations and explains the methods used to calibrate the photometry. Newly discovered variables are presented and discussed in Section 3, and the paper is summarized in Section 4.

2 Observations

Our paper is based on images acquired with the 1.0-m Swope telescope using the 2048×3150 SITE3 camera. The field of view was 14.8×22.8 arcmin² at a scale of 0.435 arcsec/pixel. Observations were conducted on 39 nights from January 5, 1998 to March 25, 2009. The same set of filters was always used. For the analysis 975 *V*-band images and 112 *B*-band images were selected. The seeing ranged from 1".2 to 3".6 and 1".2 to 2".1 for *V* and *B*, respectively, with median values of 1".5 and 1".4.

The photometry was performed using an image subtraction technique implemented in the DIAPL package.¹ To reduce the effects of PSF variability, each frame was divided into 6×4 overlapping subframes. The reference frames were constructed by combining seven images in *V* and five in *B* with an average seeing of 1".18 and 1".20, respectively. The light curves derived with DIAPL were converted from differential counts to magnitudes based on profile photometry and aperture corrections determined separately for each subframe of the reference frames. To extract the profile photometry from reference images and to derive aperture corrections, the standard Daophot, Allstar and Daogrow (Stetson 1987, 1990) packages were used. The profile photometry was also extracted for each individual image, enabling useful photometric measurements of stars which were overexposed on the reference frames, and facilitating the identification of variable objects in crowded fields (which is sometimes problematic when image subtraction alone is used). As shown in Fig. 1, the accuracy of our photometry decreases from ~ 4 mmag at $V = 14.5$ mag to 40 mmag at $V = 19.5$ mag and 100 mmag at $V = 20.5$ mag.

2.1 Calibration

M03 performed a regular transformation to the *UBV* system using their observations of Landolt standards (Landolt 1992). Since we did not have such data collected with the SITE3 camera, we decided to use their stars as secondary standards. Specifically, 679 stars with formal errors in *V* smaller than 0.015 mag were chosen, spanning a range 14 – 18 mag in *V* and 0.15 - 1.35 mag in

¹ Available from <http://users.camk.edu.pl/pych/DIAPL/index.html>

$B - V$. The linear transformations

$$V = 2.6621(3) - 0.0013(9) * (b - v) \quad (1)$$

$$B - V = 0.5521(3) + 1.0262(9) * (b - v) \quad (2)$$

proved to be entirely adequate, second-order terms did not improve the fit in any significant way. Residuals from the fit, defined as our transformed value minus the corresponding M03 value, are shown in Fig. 2. Mean and RMS values of ΔV are 0.0002 and 0.025 mag, respectively, and no systematic dependence on the color is seen. Although mean and RMS values of $\Delta(B - V)$ are also small (0.001 and 0.025 mag, respectively), for $B - V > 0.9$ mag our colors are slightly bluer than those of M03. However, since the main goal of the present survey is to detect new variables, inaccuracies of this order are unimportant. Fig. 3, based on the reference images, shows the color-magnitude diagram (CMD) of the observed field. To make the figure readable, only stars with measured proper motions (Narloch et al., in preparation) are selected to serve as a background for the variables. Stars tagged as proper-motion (PM) members of the cluster are shown in the right frame.

2.2 Search for variables

The search for variable stars was conducted using the AOV and AOVTRANS algorithms implemented in the TATRY code (Schwarzenberg-Czerny 1996, Schwarzenberg-Czerny & Beaulieu 2006). We examined time-series photometric data of 43512 stars with $V < 21.5$ mag. The limits of detectable variability depended on the accuracy of photometric measurements: the smallest amplitude we were able to measure was 0.016 mag for $14.5 < V < 15.5$ mag, and 0.35 mag for $18.5 < V < 20.5$ mag. We obtained light curves of all previously known variables within our field of view², and discovered 57 new variable or likely variable stars, 36 of which are PM-members of NGC 3201. Finding charts for the newly detected variables are shown in Figs. 4a and 4b. For completeness, we also include the finding chart for the eclipsing binary V119 of Clement et al. (2001, 2012 edition³), whose light curve we decided to publish because we detected the previously unobserved secondary minimum (as a result, the period of V119 turned out to be half or the previously reported value).

3 The new variables

Altogether, we discovered 49 periodic variables and found 8 stars suspected of variability. The basic data of this sample plus the above mentioned binary V119 are listed in Table 2. We follow the naming convention of Clement et al. (2001) and Arellano Ferro et al. (2014). The list begins with V119, and, as the last previously cataloged variable was V124, it continues from V125 on. Stars V125 – V160 are PM-members of NGC 3201, whereas VN1 – VN21 are either nonmembers or their proper motions have not been determined. The equatorial coordinates in Table 2 conform to the UCAC4 system (Zacharias et al. 2013), and are accurate to about $0''.2$.

The V -magnitudes listed in Table 2 correspond to the maximum light in the case of eclipsing binaries, while for the remaining variables average magnitudes

²Available from the CASE archive at <http://case.camk.edu.pl>

³<http://www.astro.utoronto.ca/~cclement/cat/C1015m461>

are listed. For each variable the $B-V$ color is given, followed by the amplitude in the V -band. Periods of variability were found for all stars except the suspected secular variable V160, and the eclipsing binaries V140 and VN10 for which only a part of a single eclipse was observed. The last column of Table 1 gives the membership status based on proper motions from Zloczewski et al. (2012) and Narloch et al. (in preparation). Phased light curves of the variables from Table 1 are presented in Figs. 5a – 5e. The light curve of the W UMa system V133 could not be phased with a single period. This star is analyzed in the Appendix along with W UMa systems 2 and 4 from the list of von Braun & Mateo (2002) which show the same behavior (these latter two stars do not belong to NGC 3201 according to our PM data). Some light curves are clearly periodic in one or two seasons only. In these cases we give periods obtained for the season indicated in the footnote to Table 1. A CMD of the cluster with the locations of the variables is shown in Figs. 6 and 7. The gray background stars in the CMD are the PM-members of NGC 3201 from the right frame of Fig. 3. Variables that are PM-members of the cluster are labeled in red, those with PM data indicating that they are field objects in black, and those for which the PM data are missing or ambiguous in blue.

V146, V147 and VN18 coincide with the X-ray sources X101736.16-462539.8, X101740.99-462142.1 and 3XMM J101806.9-462055 from the HEASARC Master Catalog (the corresponding coordinate differences are 0.04, 0.50 and 1.17 arcsec, respectively). Webb et al. (2006), who observed NGC 3201 with the XMM-Newton telescope, report eight X-ray sources in the field of the cluster. Of these, source #23 (= 3XMM J101715.5-462253) coincides with object #337214 on our list of light curves, located at $(\alpha, \delta) = (154.31503, -46.38146)$. Between May 2001 and June 2005 #337214 brightened in V by 1.7 mag. We took its spectrum, and it turned out it was a quasar with $V_{max} \approx 20.5$ mag, $B-V \approx 0.5$ and $z \approx 0.5$. As an extragalactic object, it is excluded from Table 2 and Fig. 6.

3.1 Detached eclipsing binaries

We detected 13 detached eclipsing binaries, of which eight are proper motion members of the cluster. Systems V138 – V142, located in turnoff or subgiant region of the CMD, are interesting targets for detailed follow-up studies aimed at the determination of their absolute parameters together with age and distance of NGC 3201. We are presently conducting such an analysis for V138, V139, V141 and V142. Their systemic velocities of 494.5, 498.3, 494.4, and 492.9 km s⁻¹, respectively, clearly confirm the membership status from Table 2. At orbital periods of 9.20, 8.79, 10.0 and 27.7 d, all four systems are well detached, so that their components should have evolved as single stars (provided, of course, that have not suffered from close encounter effects). Projected distances from the center of the cluster range from $0.2r_h$ (V141) to $1.6r_h$ (V142); r_h being the half-light radius of 3'.1 (Harris 1996, 2010 edition). The light curves of V138, V139 and V142 are stable; that of V141 shows clear signs of a vigorous activity of at least one component. Orbits of V138 – V141 are circular; that of V142 is strongly eccentric with $e=0.47$. As in this case the circularization time is longer than the Hubble time (e.g. Mazeh 2008; Mathieu et al. 2004), it is possible that the shape of the orbit has been preserved since the formation of NGC 3201 12 Gyr ago (Dotter et al. 2010). Accounting for photometry errors, the CMD-location of V140 is compatible with that of a system composed of stars with nearly the same mass. Since a part of one eclipse was only recorded, the orbital period is not known. If it is long enough, V140 will be the fifth system suitable

for a detailed analysis of component parameters.

The light curve of the turnoff binary V137 shows only one eclipse ~ 0.1 mag deep. Along with its location close to the red edge of the main sequence this suggests a rather large mass ratio of the components. The primary of this system is about to exhaust hydrogen in the core and enter the rapid expansion phase in which the mass from its envelope will be transferred to the smaller and redder secondary. Eventually, the secondary is likely to end up as another blue straggler. The period of V137 could not have been determined based on the data presented here - we took from the unpublished PhD thesis of BM. V143 is a tight lower main sequence binary with a pronounced ellipsoidal effect, too faint for spectroscopic observations given the period of only 0.38 d. V144 exhibits low amplitude ($\Delta V = 0.02$ mag) variations with $P = 0.94$ d that can be interpreted as arising from an eclipsing binary with a strong ellipsoidal effect. If this is the case, then to explain its location near the tip of the Red Giant Branch (RGB) one has to assume that the binary is blended with a red giant. Thus, despite the relatively good photometric accuracy (~ 0.005 mag, see Fig. 1), an additional confirmation of the variability of V144 is needed.

V119 is a likely PM-member of NGC 3201, whose projected location at the edge of the cluster's core additionally suggests the reality of its membership. This Algol-type system was discovered by Layden & Sarajedini (2003, their star #564), who however did not register the shallow secondary minimum, and deduced a period two times too long. Our nearly complete lightcurve (Fig. 5a) suggests a semidetached or nearly semidetached system very similar to the blue straggler V60 in M55, described in detail by Rozycka et al. (2013). If radial velocity measurements confirm the membership of V119, it will be the second example of a blue straggler “in the making”, i.e. transferring hydrogen-rich matter from the less massive, but more evolutionary advanced secondary to the primary.

VN8, for which we do not have PM data, is located within r_h . This blue system with a period of nearly three days and deep (~ 0.8 mag) eclipses must be composed of two similar subdwarfs. Seen nearly edge-on, it provides an excellent opportunity to obtain accurate parameters of its components. If radial velocity measurements confirm its membership, it will bring valuable information about late evolutionary stages of cluster binaries.

VN6, VN7 and VN10 are located on the CMD so far redwards of the main sequence that they must be foreground or background objects. Also our PM data indicate that they do not belong to NGC 3201. The light curve of VN9 is characteristic of a vigorous chromospheric activity. On the CMD this system is placed slightly bluewards of the RGB, and its projected distance of $0.9r_h$ from the center of the cluster suggests it might be a member of NGC 3201 despite our PM-measurement which seems to exclude this possibility.

3.2 Contact binaries

We identified nine variables with W UMa-type light curves of which four are PM-members of the cluster, and another three are field interlopers (for the remaining two systems no PM data are available). Small amplitudes and nearly sinusoidal variations of PM-members V134 – V136 suggest that they may be ellipsoidal variables rather than genuine contact binaries. Spectroscopic data are needed to resolve this ambiguity. The PM-member V133 has a classical W UMa lightcurve with an amplitude of ~ 0.4 mag and two total eclipses of slightly different depths. Our attempts to phase the data with a single period failed,

and an $O-C$ analysis showed that the period of this system is shortening (see Appendix for details).

These four systems all reside within r_h , strongly suggesting cluster membership. None of them is located below the main sequence turnoff, providing another example in support of the general paucity of contact binaries on unevolved main sequences of globular clusters (Yan & Mateo 1994; Kaluzny et al. 2014). At least in globular clusters, the principal factor enabling the formation of such systems from detached binaries seems to be nuclear evolution: a contact configuration is achieved once the more massive component reaches the turnoff and starts to expand, whereas the frequently invoked magnetic braking (e.g. Stepien & Gazeas 2012, and references therein) plays only a minor role. A possible exception to this rule might be VN3, located slightly redwards of the lower main sequence and about 1.5 mag below the turnoff. Its light curve is asymmetric, with maxima of different heights and minima of different depths. This suggests that VN3 is a near-contact binary of the V1010 Oph subclass (Gu et al. 2004; Shaw 1994). Unfortunately, we do not have PM data for this object, and spectroscopy remains the only means to determine its membership status.

Proper motions of VN1 and VN5 indicate that these systems do not belong to NGC 3201. The same conclusion is suggested by their position on the CMD, where they are flanking the base of the red giant branch (RGB). Most probably, they are foreground objects. VN2, a binary with a classical W UMa lightcurve, resides in the blue straggler region at a projected distance of only $0.2 r_h$ from the center of the cluster. Thus, despite the contradicting PM-evidence, we cannot exclude it being a member. Again, spectroscopy must decide. For the low-magnitude system VN4 ($\sim 21 \leq V \leq \sim 22$) we have V -photometry only, and we cannot locate it on the CMD. Its proper motion was also impossible to measure.

3.3 Variable stars among blue stragglers

In the CMD of NGC 3201 there are 266 candidate blue stragglers (BSs) with $16.0 < V < 17.7$ and $0.23 < B - V < 0.60$. Of these 140 are PM-members or likely PM-members of NGC 3201, and 19 are field stars. For the remaining 107 BS-candidates no PM data are available, but 78 of them reside at a projected distance of less than r_h from the center of the cluster. Assuming that the six candidates residing between $5r_h$ and $7r_h$ are in fact field interlopers, we may expect that 74 out of 78 candidates at $r < r_h$ are genuine BSs. Among the BS population, except the eclipsing binaries V119, V136, V136 and VN2 described in Subsections 3.1 and 3.2, we found 26 periodic variables, ten of which are new detections. V153 and V154 exhibit more or less sinusoidal luminosity variations whose nature is difficult to establish based on available data. V125 – V132 are SX Phe-type pulsators with periods ranging from 0.033 to 0.052 d. Since V129 is located about half-arcsecond away from a blue star we were not able to measure its B -magnitude; however its V -magnitude, light curve and proper motion all unambiguously determine its nature as a BS belonging to NGC3201. Altogether, 24 SX Phe stars are now known in NGC 3201; many of them bimodal.

3.4 Remaining objects

The turnoff star V145 shows clear sinusoidal variations with $P = 24.3$ d and an amplitude $\Delta V \sim 0.1$ mag. However, since it is a blend (see Fig. 4a), we marked it as a suspected variable. V146, located at the RGB and exhibiting semi-regular variations with $\Delta V \sim 0.15$ mag and $P = 13.76$ d, is a spotted variable. Similar,

but even less regular activity is observed in V147, another RGB object with a characteristic time scale of ~ 2 d. This object, like V146, coincides with an X-ray source. For V148 a clear periodicity with $P=0.47$ d and $\Delta V \sim 0.025$ mag was recorded only in our best observing season (May 2003). As such behavior is not expected for an RGB object, we classified it as a suspected variable. One of the most interesting new variables is V149, which in all seasons shows regular large-amplitude ($\Delta V \sim 0.5$ mag) sinusoidal variations with a very well defined period of only 0.062 d. A period two times longer is also acceptable, but in either case the object is apparently a tight binary composed of compact stars, probably subdwarfs. Unfortunately, the short period makes spectroscopy of V149 a very challenging task. V150 – V152 are bright stars with sinusoidal light curves of marginally detectable amplitudes and periods from 0.19 to 1.3 d. Since it is hard to give physical explanations of such behavior at their CMD-locations (horizontal branch and RGB tip), we marked all of them as suspected variables.

The turnoff object V155 with $P=0.25$ d and $\Delta V \sim 0.05$ mag may be a W UMa system seen at a low inclination angle. V156 is located at the RGB base, has $\Delta V \sim 0.03$ mag, and a very stable period of only 0.041 d. Most probably, the variable is an SX Phe pulsator blended with a red giant of about the same luminosity. The sinusoidal lightcurve of V157 has a stable period of ~ 0.17 d and an amplitude of only ~ 0.015 mag. If the marginally acceptable period two times longer were the proper one, then the star would be a blend of another red giant with a W UMa binary. V158 is a main-sequence object with $\Delta V=0.16$ mag and $P=0.2$ d. Again, if a period two times longer were the right one, another (unblended) W UMa would be the source of observed variations. Yet another W UMa, blended with a red giant/subgiant, is the only plausible explanation of regular variations with $P=0.39$ d observed in V159 – an object located at the base of the red giant branch. The photometry of V160 may be affected by a much brighter star located next to this object. The fact that its slow brightening is clearly seen in light curves obtained both with DIAPL and DAOPHOT caused us to mark V160 as a suspected variable, although physical mechanism driving such a secular change in an otherwise normal turnoff star remains obscure.

VN11, VN12, VN15, VN16, VN18 and VN21 are likely spotted background or foreground objects (VN18 coincides with an X-ray source). The remaining stars VN13, VN14, VN16, VN17, VN19 and VN20 are located at the edge of our field of view, far away from the center of NGC 3201. VN13 with $P=0.38$ d is most likely a foreground W UMa seen at a low inclination. VN14 also has a W UMa-like lightcurve, however the period (0.18 d) is too short for this class of binaries. A period two times shorter matches the data equally well. If that is the case then we are observing a strong reflection effect, and VN14 becomes a truly interesting object. The low amplitude ($\Delta V=0.02$ mag) sinusoidal lightcurve of VN17 has no straightforward interpretation. Since we cannot exclude that the observed changes are spurious, we marked this object as a suspected variable. VN19 has a very stable period of 0.092 d, and it is probably a foreground δ Scuti pulsator. The noisy lightcurve of VN20 does not allow for an unambiguous interpretation. With a marginally acceptable period two times longer than that given in Table 2, it might be a foreground W UMa seen at a very low inclination.

4 Summary

We have conducted a ten-year long photometric survey of the globular cluster NGC 3201 in a search for variable stars. A total of 49 variables plus 8 suspected variables were discovered, and multiseasonal light curves were compiled for another 95 variables that had been known before. For all observed variables periods were obtained. Three new eclipsing binaries and eight pulsating stars of SX Phe-type were found in the blue-straggler region. Twenty-four SX Phe pulsators are now known in NGC 3201, many of them multiperiodic. An asteroseismological study of the whole sample should allow a determination of BS masses and provide important constraints on theories explaining the origin of these objects. Several detached eclipsing binaries are interesting targets for follow-up spectroscopic studies from which parameters of the components can be derived together with age and distance of the cluster. Particularly valuable among these are V119 - a blue straggler most probably undergoing mass transfer from a less massive but more evolutionarily advanced secondary to the primary, and VN8 - a pair of subdwarfs on a wide three-day orbit seen nearly edge-on, which may bring important information about late evolutionary stages of cluster binaries. Another interesting object is V149 - a binary composed most likely of two subdwarfs on a very tight orbit.

Four variable objects in our field of view were found to coincide with X-ray sources. Three of them are chromospherically active stars; the fourth one is a quasar with $z \approx 0.5$ which will serve as a reference point for the determination of the absolute proper motion of NGC 3201.

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Appendix A: Period-changing W UMa stars

Attempts to fit the best period for the contact binary V133 revealed poor matching of light curves from different seasons. The same was found for another two such systems: #347900 and #451286 on our list of light curves, which had been discovered by von Braun & Mateo (2002; their stars V4 and V2, respectively). Their light curves phased with the best-fitting periods are shown in the left column of Fig. 8. Investigations reported below were conducted to check for possible period changes.

For each star first we determined the best orbital frequency ν from the multiharmonic periodogram (Schwarzenberg-Czerny 1996, 2012). In the process, by means of orthogonal projection all observations were fitted with a series of Szegő (1939) trigonometric orthogonal polynomials $p_n(z)$ of order $2N = 16$:

$$f(t) = z^{-N} \sum_{n=0}^{2N} c_n p_n(z) \quad (3)$$

where $z = e^{2\pi i \nu t}$. This real series served as our template lightcurve of fixed shape and amplitude. Next we took sets of observations from each season and by nonlinear least squares (NLSQ) we fitted them with our template by adjusting phase and zero point. As formulae for differentiation of Szegő polynomials are not readily available, we list them in Appendix B.

To protect the NLSQ solution from effects of poor phase coverage we inspected the correlation coefficient ρ between phase and zero point. Whenever $|\rho|$ exceeded 0.3, the two-parameter fit was replaced with a single-parameter one (the phase shift was only fitted). This typically occurred for the two worst-populated seasons. The zero shifts did not exceed 0.06 mag and usually were a fraction of that. Their cause is not clear; both blending and intrinsic variations are plausible explanations. Throughout the calculations we accounted for weights derived from the errors of observations. The typical scatter of observations was 0.02 mag.

The results of fitting are plotted in the right column of Fig. 8 in the form of O-C diagrams. An inspection of plots reveals large systematic phase shifts. To further investigate the trend we fitted seasonal points with parabolae. For V133 and #451286 fits were satisfactory, judging from χ^2 of order 1 per degree of freedom. For #347900 $\chi^2(4) = 6.9$ suggests possibly variable rate of period

change. The quadratic ephemerides of primary eclipses

$$HJD(Min) = T_0 + P E + \frac{1}{2} \dot{P} E^2 \quad (4)$$

corresponding to these parabolas are listed in Table 1.

Table 1: Moments of primary minima

Name	T_0	P	$\frac{1}{2}\dot{P}$
V133	2763.69610	0.270517684	1.6e-10
\pm	0.00032	0.000000023	1.5e-11
347900	2765.64121	0.441782086	-1.3e-09
\pm	0.00057	0.000000108	8.0e-11
451286	2766.70008	0.345096870	2.3e-10
\pm	0.00101	0.000000084	6.7e-11

Our results reveal period changes of both signs, on time scales P/\dot{P} ranging from -5×10^5 to 2×10^6 y, consistent with thermal time scales of binary components. Since the early ideas of Lucy (1968a, 1968b) the contact binaries are known to suffer from thermal instability due to their marginal contact. As these ideas were further elaborated by Flannery(1976), Lucy(1976) and Robertson & Eggleton(1977), a picture emerged of thermal relaxation oscillations (TRO), leading to alternate breaking and re-establishing of the contact. At some phases energy and mass could flow between the components. In particular, the period of V133 is increasing on a time scale of 2.3×10^6 y, indicating an active contact phase. While there is no evidence of orbital momentum change at this stage, stellar expansion or contraction can still lead to the corresponding period changes. Evolutionary scenarios invoke angular momentum loss during formation of W UMa systems, either during common envelope phase or due to magnetic wind (e.g. Stepien & Gazeas, 2012).

Appendix B: Differentiation of Szegő orthogonal polynomials

Expansion of orthogonal polynomials into monomials constitutes an ill posed problem, Vandermonde matrices being one example. Hence instead of trigonometric functions we employ direct derivatives of Szegő recurrence relation Eq. (10), in the process avoiding nz^{n-1} for numerical stability. Calculations can be performed by means of the recurrence starting from:

$$p_0(z) = 1 \quad (5)$$

$$p_0(z)' = 0 \quad (6)$$

$$p_0(z)^\dagger' = 0 \quad (7)$$

and continuing for $n = 0, 1, \dots, 2N$

$$c_n = \frac{(p_n, z^N x)}{\|p_n\|^2} \quad (8)$$

$$\alpha_n = \frac{(1, zp_n)}{\|p_n\|^2} \quad (9)$$

$$p_{n+1} = zp_n - \alpha_n p_n^\dagger \quad (10)$$

$$p_{n+1}^\dagger = p_n^\dagger - \overline{\alpha_n} z p_n \quad (11)$$

$$w = z(ip_n + p'_n) \quad (12)$$

$$p'_{n+1} = w - \alpha_n p_n^{\dagger'} \quad (13)$$

$$p_{n+1}^{\dagger'} = p_n^{\dagger'} - \overline{\alpha_n} w \quad (14)$$

where for $|z|=1$ dagger denotes reversion of polynomial coefficients $p_n(z)^\dagger = z^n \overline{p_n(z)}$ and apostrophe denotes derivative over phase φ , so that $z' = (e^{i\varphi})' = iz$. The scalar product is derived from times t_m and weights $w_m \geq 0$, $m = 1, \dots, M$ of observations x_m : $(f, g) = \sum_{m=1}^M w_m \overline{f(z_m)} g(z_m) \Big|_{z_m = e^{2\pi i \nu t_m}}$.

Table 2: Basic data of NGC 3201 variables discovered within the present survey*

Id	RA [deg]	DEC [deg]	V [mag]	B − V [mag]	ΔV [mag]	Period [d]	Type ^a Remarks	Mem ^b
V119	154.43733	-46.42035	16.049	0.582	0.202	2.551572	EA,BS	U
V125	154.53096	-46.36382	17.449	0.512	0.045	0.042236	SX,BS	Y
V126	154.43381	-46.34955	17.405	0.473	0.052	0.039888	SX,BS	Y
V127	154.41949	-46.40930	17.184	0.440	0.064	0.045335	SX,BS	Y
V128	154.40258	-46.39864	17.410	0.495	0.052	0.034489	SX,BS	Y
V129	154.39888	-46.38365	17.172	–	0.051	0.051988	SX	Y
V130	154.41882	-46.42159	16.357	0.477	0.021	0.047317	SX,BS	Y
V131	154.31400	-46.38674	17.244	0.462	0.041	0.033090	SX,BS	Y
V132	154.26829	-46.33185	16.551	0.430	0.103	0.047643	SX,BS	Y
V133	154.43623	-46.38333	18.305	0.645	0.369	0.270517	EW	Y
V134	154.43366	-46.40117	17.520	0.519	0.094	0.285316	EW,BS	Y
V135	154.41299	-46.40830	17.916	0.788	0.130	0.279262	EW	Y
V136	154.35266	-46.41218	16.197	0.352	0.033	0.702218	EW,BS	Y
V137	154.42977	-46.37028	17.911	0.653	0.087	7.429154 ¹	EA	Y
V138	154.36805	-46.39069	18.292	0.720	0.124	9.199380	EA	Y
V139	154.34408	-46.39947	18.076	0.716	0.297	8.789090	EA	Y
V140	154.31382	-46.41273	18.499	0.801	0.411	–	EA	Y
V141	154.38809	-46.41872	17.154	0.779	0.149	10.00370	EA	Y
V142	154.29286	-46.37735	17.257	0.756	0.108	27.69300	EA	Y
V143	154.28997	-46.46769	20.565	1.049	0.324	0.380726	EA	Y
V144	154.55648	-46.32846	14.626	1.066	0.025	0.938225 ²	EB?	Y
V145	154.45097	-46.48473	18.133	0.679	0.110	24.34624	?	Y
V146	154.37700	-46.41179	17.275	0.932	0.158	13.75904 ¹	SP,RG	Y
V147	154.33856	-46.43918	17.410	0.757	0.124	1.910503 ³	SP?	Y
V148	154.54247	-46.31482	17.235	0.889	0.040	0.467678 ⁴	?	Y
V149	154.50747	-46.36550	21.280	0.701	0.485	0.062268	EB?	Y
V150	154.51355	-46.39422	15.225	0.322	0.016	0.18642 ²	?	Y
V151	154.40944	-46.33032	14.275	1.043	0.021	1.033544 ³	?	Y
V152	154.39568	-46.32713	14.692	0.756	0.018	0.516789	?	Y
V153	154.41524	-46.36521	17.592	0.484	0.089	0.899928 ³	?	Y
V154	154.36395	-46.39678	16.498	0.321	0.024	0.168045 ⁴	?	Y
V155	154.35480	-46.42202	17.690	0.670	0.056	0.252956	EW?	Y
V156	154.39468	-46.44167	17.084	0.840	0.029	0.041316	SX?	Y
V157	154.38582	-46.44596	15.651	0.916	0.016	0.174603	EW?	Y
V158	154.34077	-46.44567	19.501	0.805	0.162	0.199170	EW?	Y
V159	154.29128	-46.38593	17.392	0.894	0.028	0.387159	EW?	Y
V160	154.44577	-46.48059	17.695	0.611	0.170	2100.000 ⁵	LPV	Y
VN1	154.41641	-46.39019	17.682	0.856	0.113	0.398926	EW	N
VN2	154.40006	-46.42012	17.702	0.533	0.359	0.297544	EW,BS?	N
VN3	154.43425	-46.47440	19.660	0.924	0.384	0.336212	EW	U
VN4	154.40413	-46.44006	21.713	–	0.905	0.398336	EW	U
VN5	154.27474	-46.34356	17.197	0.785	0.154	0.286946	EW	N
VN6	154.54876	-46.31227	18.576	0.868	0.104	1.063468	EA	N
VN7	154.53385	-46.45677	20.570	1.430	0.464	0.967542	EA	N
VN8	154.42951	-46.37056	20.641	0.602	0.693	2.860388	EA	U
VN9	154.45077	-46.44544	16.441	0.759	0.087	8.909326	EA	N
VN10	154.27129	-46.56679	17.641	0.924	0.326	–	EA	N
VN11	154.43976	-46.45586	17.521	0.581	0.111	4.341275	SP	N
VN12	154.49269	-46.47945	14.355	0.922	0.026	23.84405	SP	N
VN13	154.50828	-46.26136	15.780	0.846	0.019	0.377768	EW?	N
VN14	154.49405	-46.21687	19.967	1.502	0.389	0.088603	EW?	U
VN15	154.46060	-46.28940	17.623	1.255	0.140	15.95484	SP?	N

*We follow the naming convention of Clement et al. (2001; 2012 edition) continued by Arellano Ferro et al. (2014), whose last cataloged star was V124. V119 is additionally listed as a system for which we provide important new information. Stars VN1 – VN22 are either not PM-members of NGC 2301 or PM data are missing for them.

^aEA: detached eclipsing binary, EB: close eclipsing binary, EW: contact eclipsing binary, SX: SX Phe-type pulsator, SP: spotted variable, LPV: long-period variable, ?: roughly sinusoidal variations of unknown nature, BS: blue straggler, RG: red giant.

^bY: member, N: nonmember, U: no data or data ambiguous.

¹Period taken from the unpublished PhD thesis of BM. ²Periodicity may be spurious.

³Irregular variations are also possible. ⁴Clear periodicity observed in May 2003 only. ⁵Period is the time-span between the first and the last observation.

Table 2 concluded

Id	RA [deg]	DEC [deg]	V [mag]	$B - V$ [mag]	ΔV [mag]	Period [d]	Type Remarks	Mem ^b
VN16	154.56195	-46.36209	16.075	0.884	0.030	1.123061	SP?	N
VN17	154.55929	-46.38112	15.375	0.886	0.022	0.493302	?	N
VN18	154.52895	-46.34859	16.566	1.233	0.035	7.862955	SP?	N
VN19	154.55825	-46.45848	14.668	0.635	0.030	0.092057	?	N
VN20	154.59523	-46.48295	14.653	0.596	0.016	0.166173	?	U
VN21	154.30577	-46.37241	18.590	1.179	0.084	7.299531	SP?	N

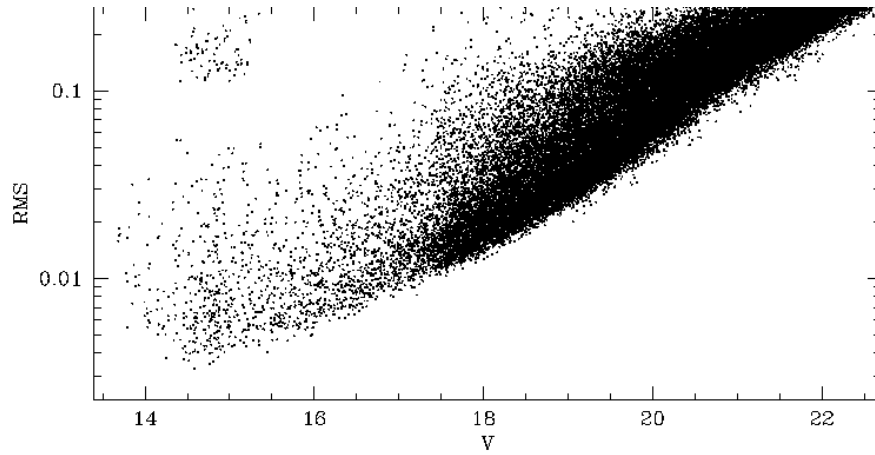


Figure 1: Standard deviation vs. average V magnitude for light curves of stars from the NGC 3201 field. The points spread around $RMS \approx 0.15$ and $V \approx 15$ mag are RR Lyr stars.

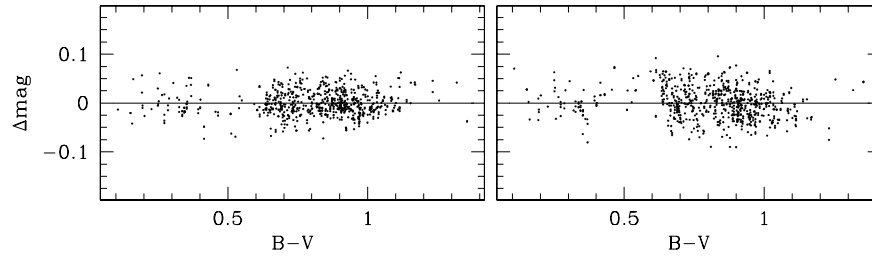


Figure 2: Differences between our photometry transformed to the standard system and that of M03. V -magnitudes and $B - V$ colors of 679 stars are compared in left and right panel, respectively.

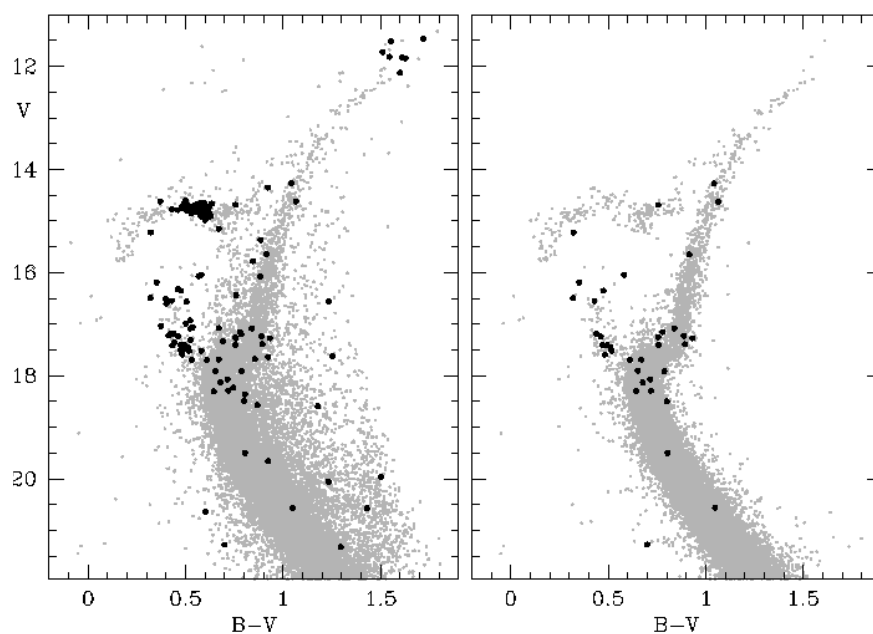


Figure 3: CMD of NGC 3201. Left: all stars within our field of view for which proper motions were measured. Black points mark all variables detected within the present survey. Right: PM-members of the cluster only. Black points mark the newly detected variable members of NGC 3201.

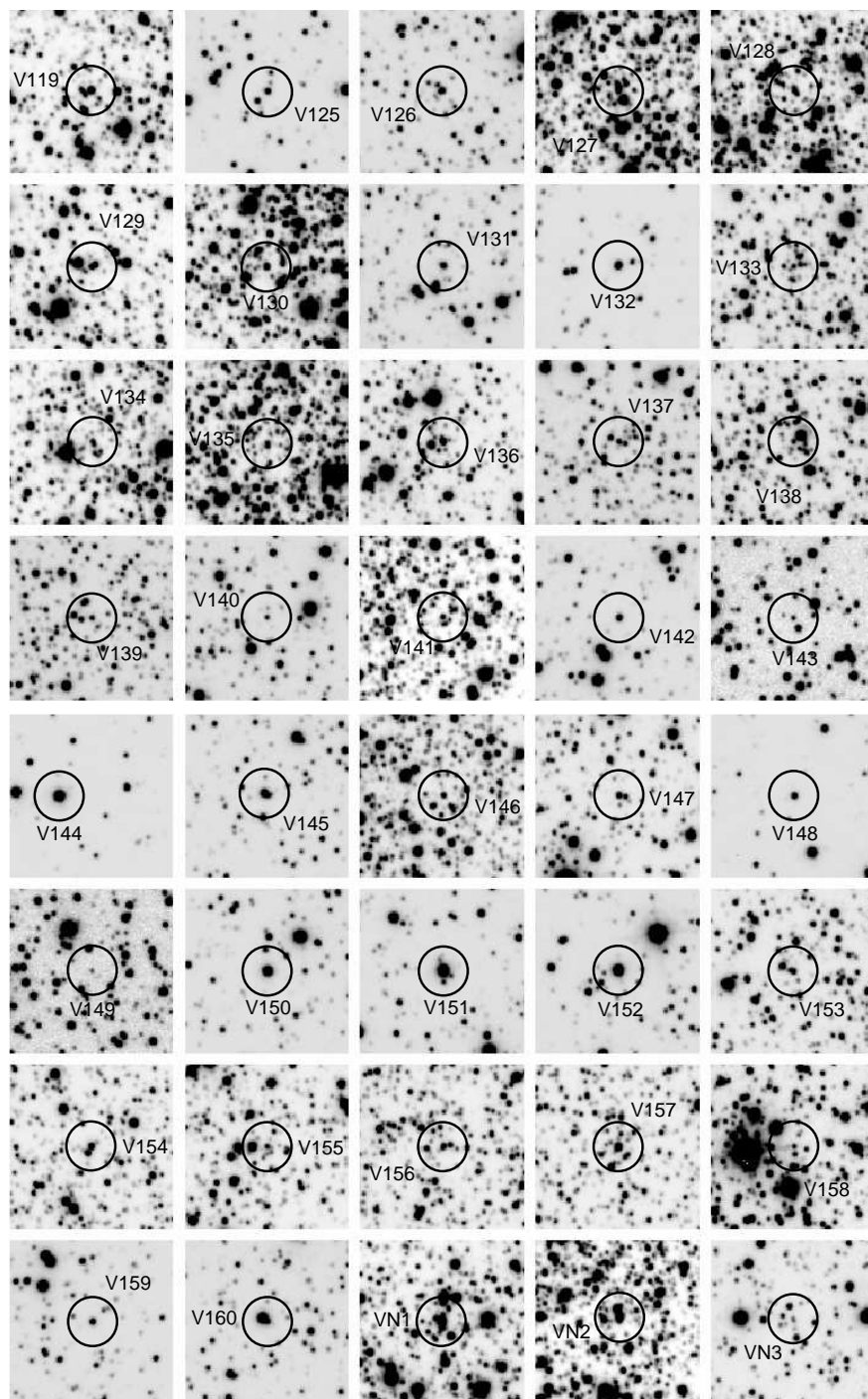


Figure 4a: Finding charts for the variables. Each chart is 30 arcsec on a side; north is up and east to the left.

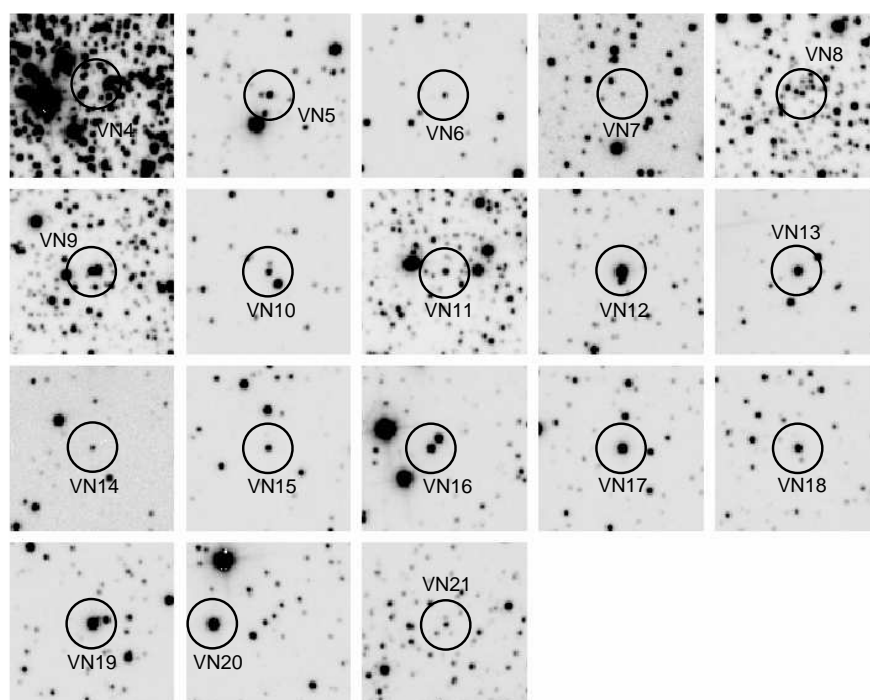


Figure 4b: Continuation of Fig. 4a.

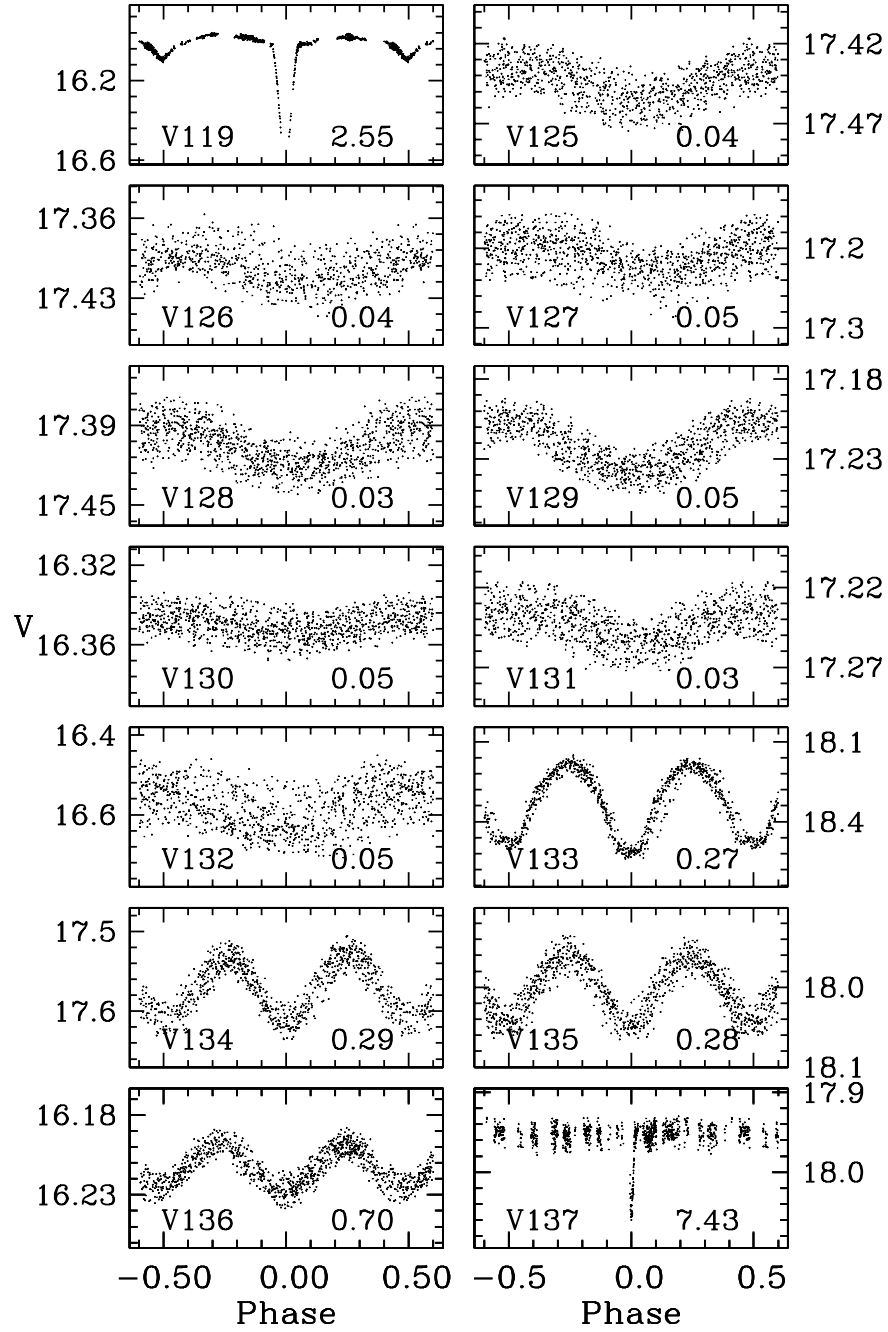


Figure 5a: Phased V curves of variables detected in the field of NGC3201. Inserted labels give star ID and period in days.

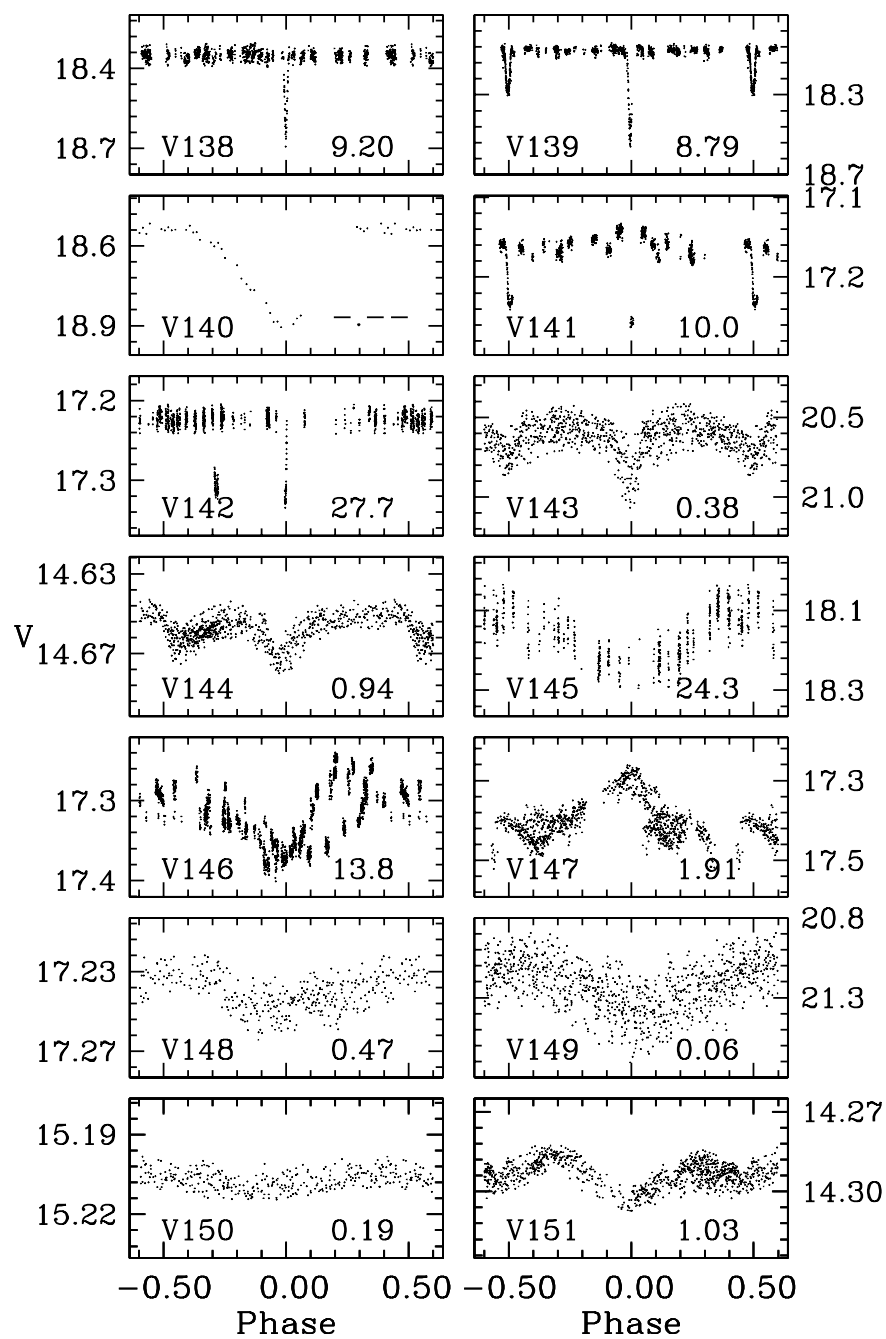


Figure 5b: Continuation of Fig. 5a.

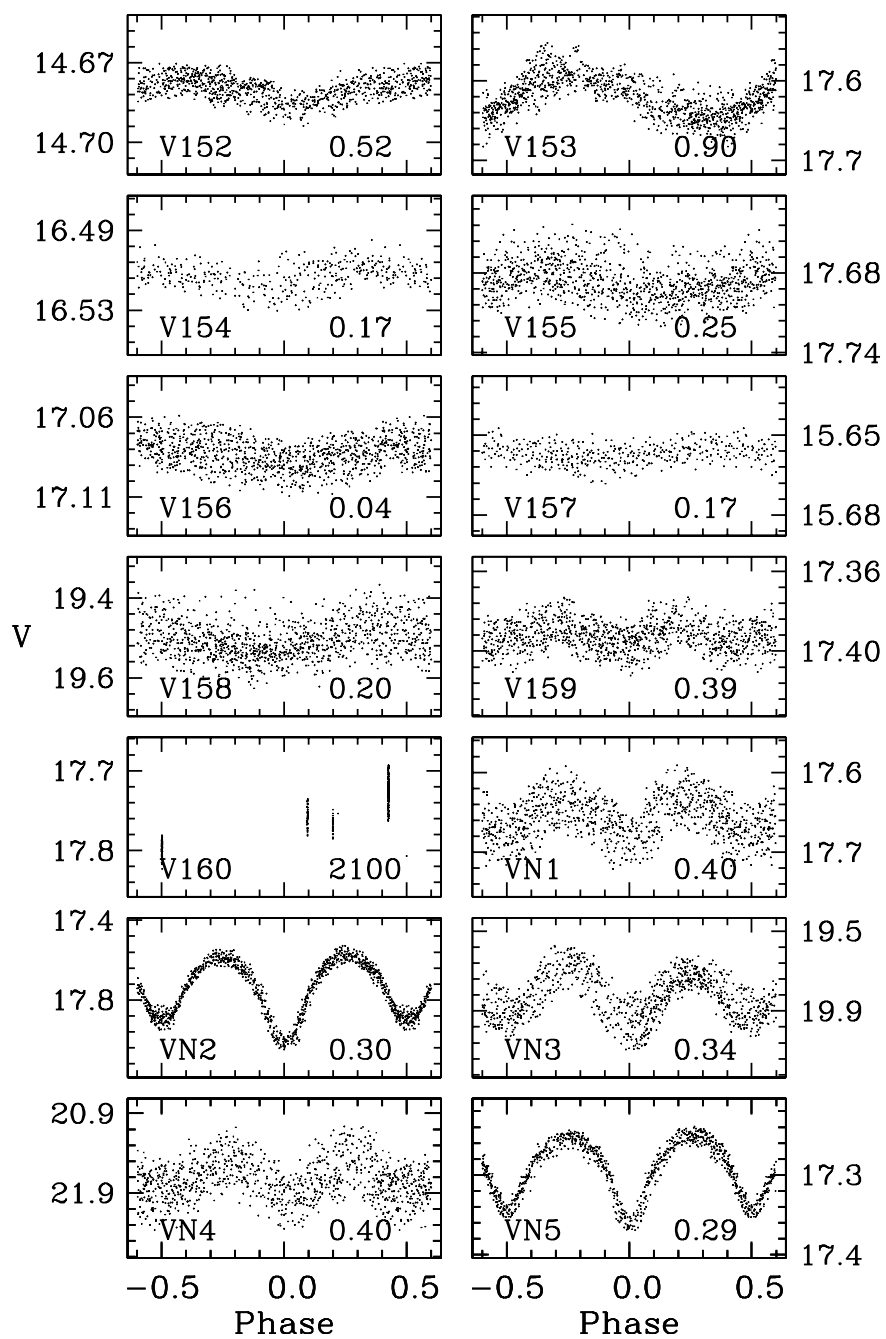


Figure 5c: Continuation of Fig. 5a.

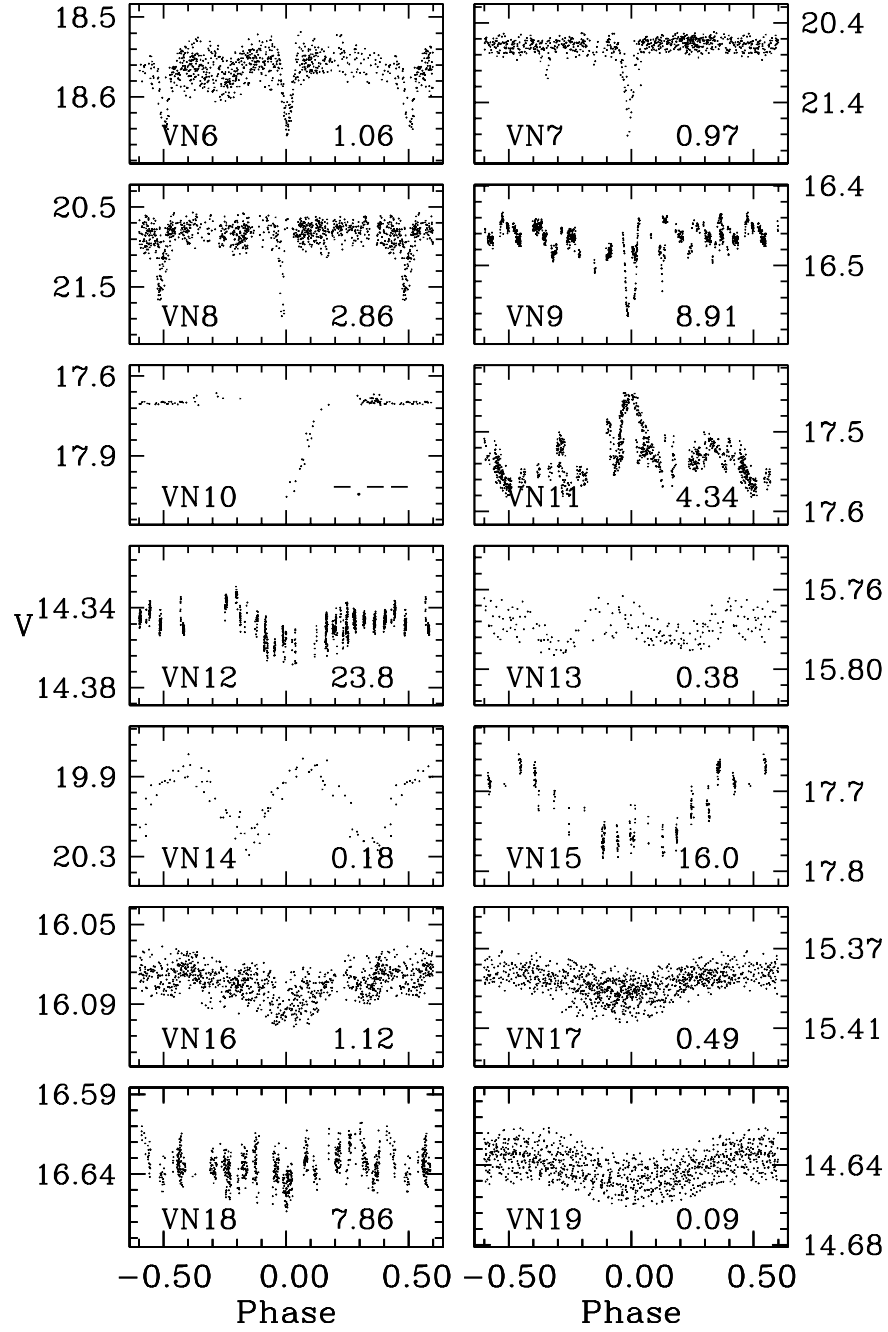


Figure 5d: Continuation of Fig. 5a.

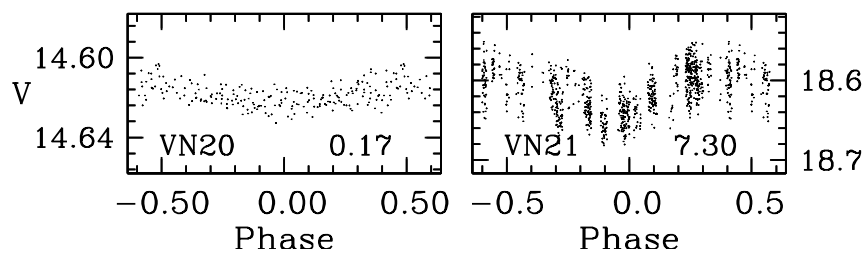


Figure 5e: Continuation of Fig. 5a.

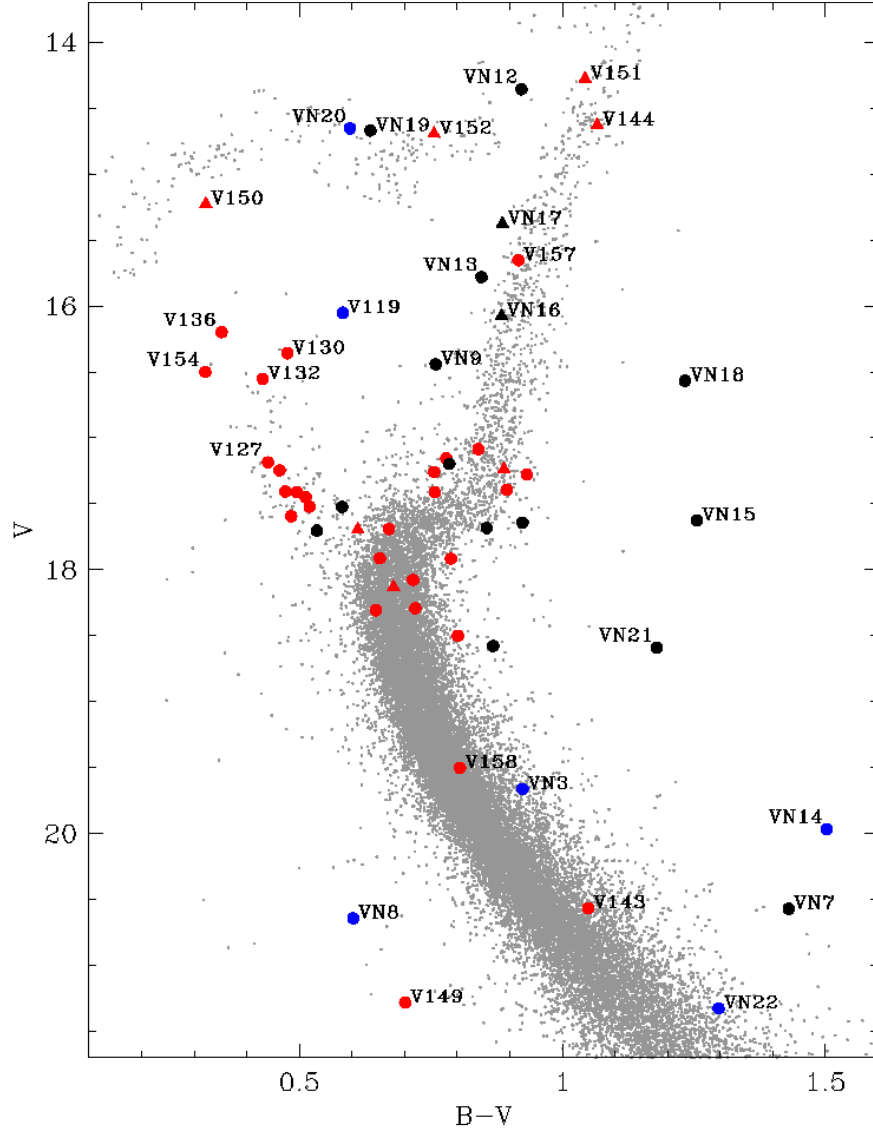


Figure 6: Color-magnitude diagram for NGC 3201 with indicated locations of newly detected variables. Red, black and blue symbols denote, respectively, members, nonmembers and objects for which the PM-membership data is missing or ambiguous. Circles: periodic variables. Triangles: suspected variables. The gray background stars are the same as in the right frame of Fig. 3. The central part of the diagram is shown magnified in Fig. 7.

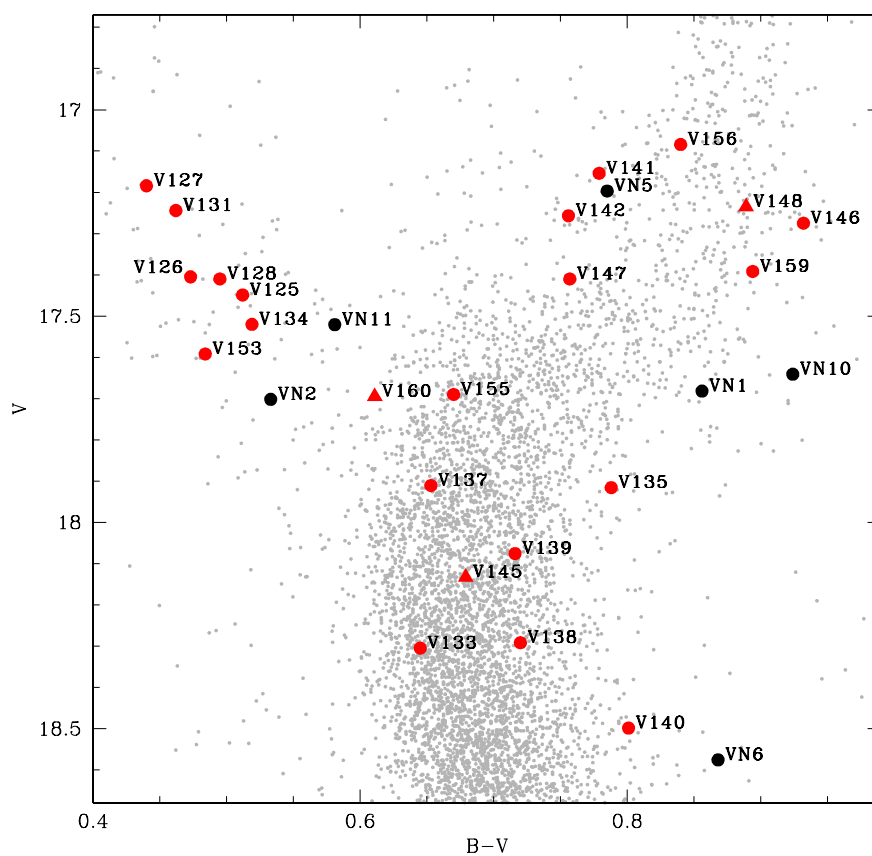


Figure 7: The turnoff region from Fig. 6.

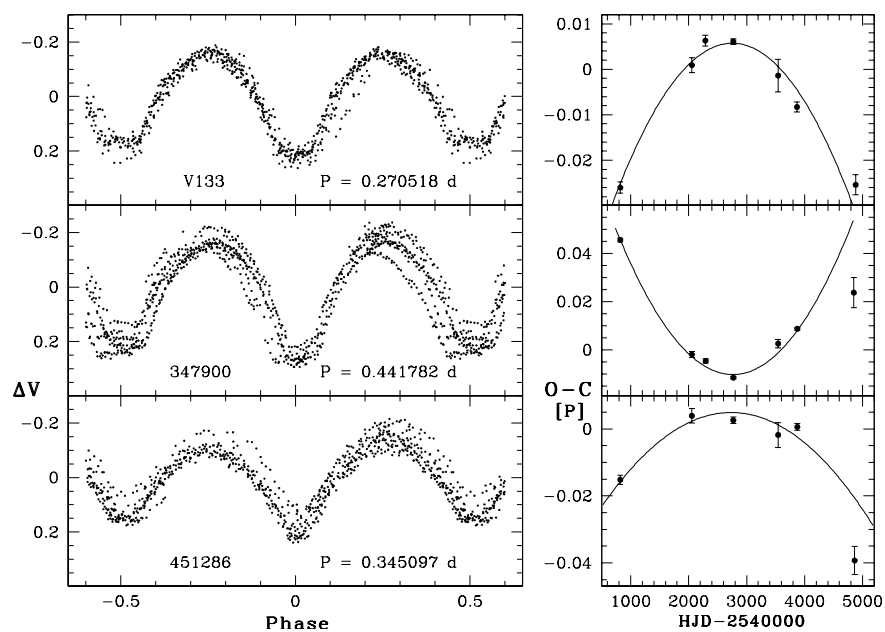


Figure 8: Left column: light curves of period-changing W UMa binaries phased with the best-fitting constant periods. Stars #347900 and #451286 were discovered by von Braun & Mateo (2002) who listed them as V4 and V2, respectively. Right column: O-C diagrams for these systems.